

# **Mesoscale Processes In Tropical Cyclones**

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## **LONG-TERM GOALS**

Our long-term goals are to develop improved understanding and prediction of the atmosphere, with particular emphasis on tropical cyclones. Our work encompasses research into basic processes, field programs, and development of forecast and impacts reduction systems.

## **OBJECTIVES**

To investigate the impact of mesoscale processes on the motion and development of tropical cyclones by theoretical and modeling studies and by the gathering and diagnosis of data.

## **APPROACH**

We have adopted a stratified research approach, including use of quasi-analytic methods to provide hypotheses and indications of the potential processes, followed by application to sophisticated numerical experiments and diagnostic examination of actual tropical cyclones.

## **WORK COMPLETED**

We have made substantial progress on documenting and understanding several aspects of tropical cyclone motion and development during this research program. Work completed in previous years includes: a comprehensive analysis of the manner in which atmospheric vortices can interact; the

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first research results on the presence of mesoscale vortices in tropical cyclones and their effect on motion and development; an explanation for the tendency of cyclones to meander about a mean path; a comprehensive analysis of the manner in which a cyclone interacts with the larger-scale circulations to influence tropical cyclone formation and initial development; analysis of the baroclinic effects on tropical cyclone motion; thermodynamic estimation of tropical cyclone intensity, which has been utilized in a WMO statement on climate change and tropical cyclones; the first assessments of the effects of spray on tropical cyclones and examination of boundary-layer processes on tropical cyclone structure and development; an analysis of the predictability of tropical cyclone tracks; the mechanisms that limit tropical cyclone intensification; Global Guide to Tropical Cyclone Forecasting; and several forecasting techniques.

During 2000 we have continued efforts to establish the ***International Tropical Cyclone Landfall Program*** through the USWRP and the World Weather Research Program and the Tropical Meteorology Research Program of the World Meteorological Organization. The focus is on wind fields and rainfall. The windfield component has been identified as of prime importance to Navy requirements and includes continued work on track, intensity and structure changes. We have stabilized the observing suite at the ***Northwest Cape Boundary-Layer Observing Site***. This site has been visited by two tropical cyclones and is being maintained as a major boundary layer observing site. The ***Tropical Cyclone Model (tropical cycloneM3)*** has been made available to researchers at the Universities of Hawaii and Jackson State. This high resolution, triply nested model continues to be a major factor in our research programs and has been upgraded to include improved cloud physics and boundary-layer processes.

## RESULTS

During 2000 we continued our research focus on the mechanisms that limit tropical cyclone intensity, the boundary-layer structure under high wind conditions and predictability of tropical cyclones.

***Boundary layer flow within intense vortices:*** Previously, we have analysed the features of the flow within the tropical cyclone boundary layer using analytical and full numerical model methods. We found that the boundary layer flow can be largely understood as the superposition of three components: a symmetric one due to the cyclone itself, and two asymmetric components due to the interaction of the cyclone with the underlying surface. The symmetric component has a depth that decreases from 1000-2000 m in the periphery to ~300 m in the core. The two asymmetric components have distinct depth and amplitude scales. Relative to the symmetric component, one asymmetric component is shallower and much weaker and the other is several times deeper in the core and of comparable strength. The analytical and numerical models are similar, differing only in the neglect of vertical advection and other nonlinear processes in the analytical model. Expressions were derived for a range of meteorologically interesting and operationally significant parameters, including boundary layer depth, height of the low level jet, vertical motion, and near-surface wind speed. These are expected to have substantial operation utility.

We have now commenced a comparison of these predictions with observations, both from our own site at North West Cape (discussed further below), and elsewhere. Our theoretical predictions have shown considerable skill in explaining the structure of observed wind profiles. For instance, our model initialised with the surface pressure field and movement of Hurricane Georges correctly reproduced the vertical profiles of wind speed from eight dropwindsondes deployed in the eye wall. This work, which is in collaboration with Kevin Knupp and James Franklin, clearly indicates that we are capturing not just the character of the jet, but also its substantial spatial variability.

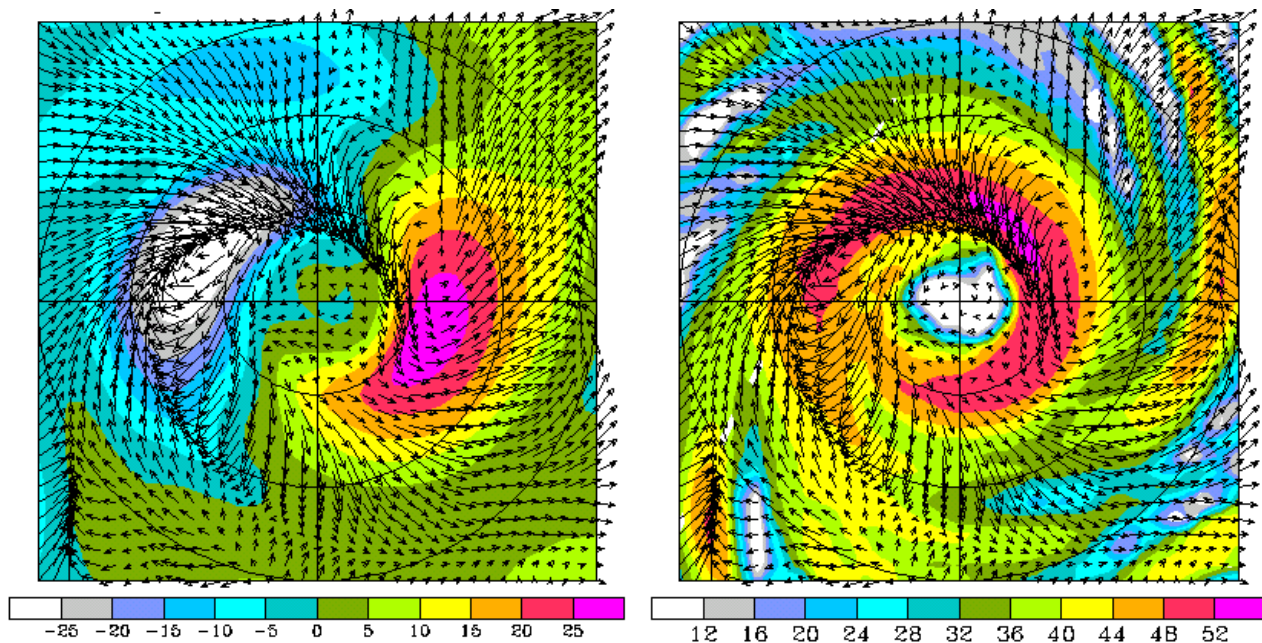
***Impact of sea spray evaporation on tropical cyclone intensification and intensity:*** Numerical simulations using tropical cycloneM3 have shown that invoking the spray parameterizations of Fairall et al (1995) and Andreas and DeCosmo (1999) produce radically different results. In the former case, the intensity of the storm is barely changed, although there are some detail effects on the boundary layer structure. The latter parameterization leads to a marked increase in the storm intensity. This was found to be due to differing assumptions in the respective parameterizations on how the boundary layer adjusts to the droplet-mediated fluxes immediately adjacent to the sea surface. Comparison with results from our explicit droplet evaporation and transport model suggests that the Fairall et al provides the more realistic results. It was also found that some aspects of the sea-spray response were affected by details of other parameterizations within the model. In particular, the use of a full mixed-ice phase cloud microphysics scheme in the generation of downdrafts outside of the cyclone core, and a greater spray impact in the relatively warm moist boundary layer there.

***The North West Cape Boundary Layer Observing Station*** has now collected data in two tropical cyclones. Profiler and sonic anemometer data were collected up to shortly before the landfall of Severe Tropical Cyclone Vance in March 1999 (when power was lost), while the weak and disorganized Tropical Cyclone Steve passed about 100 km inland about a year later. This latter case produced an interesting case of stable gale-force flow off the rain-cooled land. Pressure data taken in Vance, together with the observed movement, were used to force our boundary layer model, and the predicted flow compared very well with the observations. The observed wind speed at the jet core was about 15% supergradient in both observations and the model results. Initially, the predicted near-surface winds were somewhat stronger than was observed by our tower-mounted sonic anemometers. This was found to be due to the use of the standard open-ocean, long fetch Charnock coefficient of 0.011 in the model. Increasing this to 0.05 or even 0.10 gave much better agreement. It is an open question as to how much of this increase may be attributed to the shallow waters of the Exmouth Gulf, and how much to the short fetch, non-equilibrium wave field in a tropical cyclone. It does however suggest that care is needed in parameterizing surface processes at landfall.

***Rossby waves on the cyclone vortex:*** We have completed a comprehensive model diagnosis of vortex Rossby waves within the cyclone core region and their role in both intensity and structure changes and eye-wall scale oscillations. Recent studies (e.g., Montgomery and Lu 1997; Montgomery and Kallenbach 1997; Montgomery and Enagonio 1998) have indicated the potential importance of vortex Rossby waves in tropical cyclone dynamics. These barotropic studies neglect potentially important baroclinic and moist convective interactions. For example, potential vorticity (PV) anomalies can generate asymmetries in convection, which in turn modify the PV anomalies in a non-linear and complex manner. We have found that the vortex Rossby waves are dominated by wave-number one and two, tilt outward with height, and possess quasi-balanced dynamical features in the mid-lower troposphere (Wang 2000). The waves are advected cyclonically but move slower than the mean flow. The phase speed is anticyclonic and outwards and there is inwards energy dispersion. Consistent with Montgomery and Franklin (1998), the perturbation vorticity and divergence associated with the vortex Rossby waves have similar amplitude even in the core region. This convergence-divergence is the main source for vorticity generation, which is nearly balanced by the radial advection of the vorticity of the primary cyclone by the asymmetric flow associated with the waves.

The vortex Rossby wave evolution is a major factor in initiating inner spiral rain bands and producing polygonal eye wall structure and its cyclonic rotation. They can result in a breakdown of the eye wall and substantial weakening and subsequent re-intensification of the cyclone. The

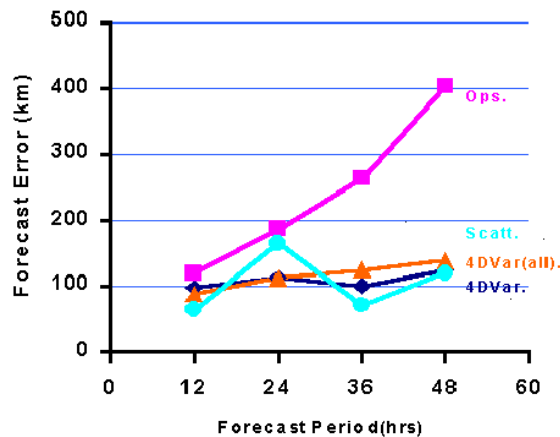
cyclonic rotation of the wave number-one vortex Rossby waves along the eye wall also results in a cyclonic rotation of the cyclone motion at an eye wall scale.



**Figure 1.** *The vortex Rossby wave signature at the 850 hPa level: Left is the asymmetric geopotential height, right is the total radar reflectivity and the asymmetric horizontal winds relative to the moving cyclone are superimposed on both. The cross shows the model tropical cyclone center and circles are at radii of 30, 60, and 90 km.*

**Inherent Predictability of Tropical Cyclones:** Work has now been completed on the assessment of how close current NWP models are to the limit of predictability for tropical cyclones. The chaotic nature of the systems and the governing equations results from the non-linearity and the multifarious feedback processes that take place in such complex systems. The FY00 results confirm our initial assessment that there is still a large gap of somewhere between 35 to 50% in what is being achieved at present and what is possible. Thus, the model forecast errors of tropical cyclone track position could be *halved* in the future.

Figure 1 shows the potentially large further gains being made in track error reduction for a set of 12 difficult tropical cyclones. Much of the improvement has been a result of improved data coverage. It is anticipated that considerable reductions will be obtained in tropical cyclone track errors over the next few years as a result of continued improvements in data assimilation procedures, better data coverage and quality and improved model formulation and resolution. Continuing work is aimed at estimating the inherent errors of tropical cyclone intensity and intensity change.



**Figure 2: Comparison of tropical cyclone track errors for 12 “difficult” tropical cyclones. Operational results are seen to be greatly improved by the use of high-resolution 4-D data assimilation schemes, which take advantage of an enhanced database.**

Earlier work has shown that the use of bogus cyclones to initialise numerical models can lead to major problems. By using a long period of numerical experiments with a range of resolutions, data assimilation techniques and model formulations and resolutions, LeMarshall and Leslie (1999) and Leslie and LeMarshall (2000) have demonstrated that realistic intensification of tropical cyclones can be obtained by utilising high temporal and spatial resolution data during assimilation, an effective initialization procedure, and very high resolution. The results of this work have been referred to as “pioneering” by WMO and were reported on in the December 1999 meeting of the WMO COMPARE Committee.

## IMPACT/APPLICATIONS

Our strategic research is aimed at improved understanding and improved predictability of the intensity and movement of tropical cyclones. To ensure good feedback with operational staff, we maintain a regular program of seminars and discussions at major operational centers and meetings. The ONR program has had considerable direct and indirect impacts on the international science and operations through its high profile amongst various WMO forums, including the meetings of the WMO Tropical Cyclone Program and the International Workshops on Tropical Cyclones. As part of this effort we lead the publication of the Global Guide to Tropical Cyclone Forecasting (Holland et al., 1993). The predictability studies have explicitly shown that there remains much to be gained by improved modeling and data gathering for tropical cyclone prediction.

## TRANSITIONS

The group is interacting closely with a number of groups in the United States and internationally, including the Universities of Hawaii, Colorado and Rhode Island, NASA Goddard, and the NOAA/AOML Hurricane Research Division.

The TCM3 model also has been installed at the Universities of Hawaii, Jackson State and Rhode Island, to support their research on tropical cyclones. Our explicit cloud microphysics scheme has been implemented into the HIRES model at the University of New South Wales University and the LAPS model at BMRC. The MPI technique has been used for a statement on climate change by the World Meteorological Organization (Henderson-Sellers et al, 1997) and for a direct comparison to numerical modeling studies of climate change by the NOAA GFDL. We have prepared an

extensive set of fields based on the NCEP reanalysis for research project by Chris Velden at Wisconsin.

## RELATED PROJECTS

The Aerosonde Development Program (see separate report) is moving to tropical cyclone missions next year, with provision of data for continuing our research activities. The WMO International Tropical Cyclone Landfall Program is geared to provide an international focus on the tropical cyclone boundary layer, track and intensity changes with an emphasis on processes relevant to landfall.

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